(54) Title: METHOD FOR TELEMANIPULATION WITH TELEPRESENCE
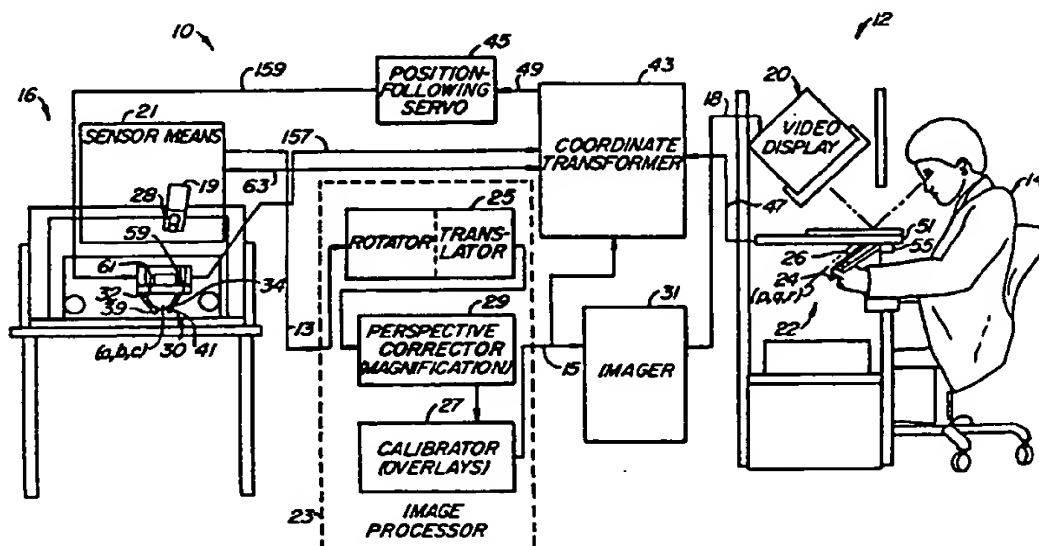
(57) Abstract

In a telemanipulation system (12) for manipulating objects located in a workspace at a remote worksite by an operator (14), such as in a remote surgical system, the remote worksite having a manipulator with an end effector (39) for manipulating an object at the workspace, a controller including a hand control (22) at the operator's station for remote control of the manipulator, an image capture device (19), and image output device (20) for reproducing a viewable real-time image, the improvement wherein a position sensor associated with the image capture device (19) senses position relative to the end effector (39) and a processor (23) transforms the viewable real-time image into a perspective image with correlated manipulation of the end effector (39) by the hand controller (22) such that the operator can manipulate the end effector and the manipulator as if viewing the workspace in true presence. Image transformation according to the invention includes translation, rotation (25) and perspective correction (29).

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5   METHOD FOR TELEMANIPULATION WITH TELEPRESENCE

                          BACKGROUND OF THE INVENTION
                   This invention relates to telemanipulation using
           telepresence, and more particularly to applications of
10   telemanipulation to laparoscopic surgery.
                   A telemanipulation system allows an operator to
           manipulate objects located in a workspace from a remote
           control operator's station. For example, in a laparoscopic
           abdominal surgery procedure, the patient's abdomen is
15   insufflated with gas, and cannulas are passed through small
           incisions to provide entry ports for laparoscopic surgical
           instruments. Laparoscopic surgical instruments include an
           image capture means for viewing the surgical field and working
           tools, such as forceps or scissors. The working tools are
20   similar to those used in open surgery, except that the working
           end of each tool is separated from its handle by an extension
           tube. The surgeon performs surgery by sliding the instruments
           through the cannulas and manipulating them inside the abdomen
           while referencing a displayed image of the interior of the
25   abdomen. Surgery by telepresence, that is, from a remote
           location by means of remote control of the surgical
           instruments, is a next step. A surgeon is ideally able to
           perform surgery through telepresence, which, unlike other
           techniques of remote manipulation, gives the surgeon the
30   feeling that he is in direct control of the instruments, even
           though he only has remote control of the instruments and view
           via the displayed image.
                   The effectiveness of telepresence derives in great
           measure from the illusion that the remote manipulators are
35   perceived by the operator of the system to be emerging from
           the hand control devices located at the remote operator's
           station. If the image capture means, such as a camera or
           laparoscope, are placed in a position with respect to the

manipulators that differs significantly from the
anthropomorphic relationship of the eyes and hands, the
manipulators will appear to be located away from the
operator's hand controls. This will cause the manipulators to
5   move in an awkward manner relative to the viewing position,
inhibiting the operator's ability to control them with
dexterity and rapidity. However, it is often unavoidable in
applications such as laparoscopic surgery to move the
laparoscope in order to obtain the best possible image of the
10   abdominal cavity.

        Thus, a technique is needed for providing to the
operator the sense of direct hand control of the remote
manipulator, even in the presence of a substantially displaced
imaging device, such that the operator feels as if he is
15   viewing the workspace in true presence.

                    SUMMARY OF THE INVENTION
        According to the invention, in a telemanipulation
system for manipulating objects located in a workspace at a
20   remote worksite by an operator at an operator's station, such
as in a remote surgical system, the remote worksite having a
manipulator or pair of manipulators each with an end effector
for manipulating an object at the workspace, such as a body
cavity, a controller including a hand control at the control
25   operator's station for remote control of the manipulators, an
image capture means, such as a camera, for capturing in real-
time an image of the workspace, and image producing means for
reproducing a viewable image with sufficient feedback to give
the appearance to the control operator of real-time control
30   over the object at the workspace, the improvement wherein
means are provided for sensing position of the image capture
means relative to the end effector and means are provided for
transforming the viewable real-time image into a perspective
image with correlated manipulation of the end effector by the
35   hand control means such that the operator can manipulate the
end effector and the manipulator as if viewing the workspace
in substantially true presence. By true presence, it is meant
that the presentation of an image is a true perspective image

simulating the viewpoint of an operator. Image transformation
according to the invention includes rotation, translation and
perspective correction.

     The invention will be better understood by reference
5   to the following detailed description in connection with the
accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

     Fig. 1A is a side view of a remote operator station
10   and of a worksite station in a telemanipulation system
according to the present invention.

     Fig. 1B is a perspective view of a remote operator
station and a worksite station adapted for stereoscopic
viewing in a telemanipulation system according to the present
15   invention.

     Fig. 2 is a diagrammatic perspective view of a
specific embodiment of the invention wherein the image capture
means is centered and normalized relative to the viewpoint of
an operator using the manipulators.

20   Fig. 3 is a diagrammatic perspective view of a
specific embodiment of the invention wherein the image capture
means is laterally displaced relative to the viewpoint of an
operator using the manipulators.

     Fig. 4 is a diagrammatic perspective view of a
25   specific embodiment of the invention wherein the image capture
means is at a lower position relative to the viewpoint of an
operator using the manipulators.

     Fig. 5A is a front elevational view of the lenses of
a stereoscopic image capture means where the lenses are in a
30   normalized position relative to the viewpoint of an operator
using the manipulators.

     Fig. 5B is a front elevational view of the lenses of
a stereoscopic image capture means where the lenses are
rotated relative to the viewpoint of an operator using the
35   manipulators.

     Fig. 6A is a top plan view of an image of a remote
manipulator in a telemanipulation system that shows a

superimposed stereographic four-point coordinate element prior
to calibration.

Fig. 6B is a top plan view of an image of a remote
manipulator in a telemanipulation system that shows a
superimposed stereographic four-point coordinate element after
calibration.

Fig. 7A is a top plan view of an image of a remote
manipulator in a telemanipulation system that shows the angle
of displacement in the horizontal of the image capture means
relative to the manipulators.

Fig. 7B is an enlarged view of a portion of Fig. 4A
that shows the combined effect on the position of the end
effector of a manipulator after a lateral shift.

Fig. 8 is a geometric depiction of the image of a
manipulator as a projection of a hand control.

Fig. 9 is a geometric depiction of the actual
manipulator whose image is depicted in Fig. 8.

DESCRIPTION OF SPECIFIC EMBODIMENTS

Fig. 1A shows a telemanipulation system 10 according
to the present invention with a remote operator station 12
where an operator 14 (a surgeon, for example) can perform
telemanipulation on an object at a worksite station 16. The
remote station 12 includes a video display 20 for the operator
14 to view the worksite and an apparent workspace 22 where the
operator 14 carries out the actual manipulations by grasping
hand control means 24, 26, such as surgical instrument
handles, which are connected to position sensors 51, 55. The
worksite station 16 includes an image capture means 19,
including a sensor means 21 with camera lens 28 of a camera or
endoscope and understanding that there is an image capture
means 19 associated with that lens, which captures an image of
an object located in the workspace 30. (An endoscope would be
within the body cavity.) The manipulators 32, 34 allow
manipulation of the object in the workspace 30 correlated with
a displayed image by use of end effector means 39, 41.

The image captured at worksite 16 is transmitted
through a number of stages which present to operator 14 a

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real-time image of the object in the workspace 30. In
particular, sensor means 21, including optical image capture
means 19, provides a view of the manipulators 32, 34 through a
camera lens 28, passing such image information via path 13 to

5   an image processor 23. In addition, image sensor position
information (camera position) may be passed on path 63 to
coordinate transformer 43. (For a fixed camera, the camera
position information can be preset). Further, mechanical
position sensing means 59, 61 sense the position of

10   manipulators 32, 34 mechanically, passing on the position
information to coordinate transformer 43 via path 157.

The image processor 23 includes a rotation and
translation means 25, a perspective correction means 29 and a
calibration means 27. The rotator is for rotating the image

15   and the translator is for shifting the rotated image. The
perspective corrector 29 is primarily for magnifying the image
and may include some tilt correction. The calibrator 27 may
have various functions, depending upon the type of image
input. It is in particular used to calibrate the image to a

20   known reference coordinate system to enable an operator to
coordinate motions of the hand controls and the manipulators.
After the image has undergone transformation through one or
more of these function blocks, the pixel data is passed on
path 15 to an imager 31 which drives a video display 20, which

25   in this embodiment is a monoscopic device, and data about the
image is passed on to the coordinate transformer 43, whereby
any processed image data potentially affecting control of the
manipulators (e.g., magnification, rotation, translation) is
made available for the control of the manipulators. The

30   details of the processes which may be affected are explained
hereinbelow, particularly with respect to calibration.

The coordinate transformer 43 is the principal
processor of position information. Camera position
information, manipulator position information, and hand

35   control position information are received and processed
therein. In particular, the positions of hand controls 24, 26
are sensed by position sensors 51, 51 and passed via path 47
to coordinate transformer 43. After transformation and

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processing in coordinate transformer 43, control information
is applied to position-following servo 45, which drives and
controls manipulators 32, 34 with end effectors 39, 41. The
operation of each of these blocks will be described in further
5   detail.

In operation, the camera lens 28 captures the image
of the object in the actual workspace 30 in a specific
orientation on image capture means 19. The video display 20
displays this image so that the operator 14 can view the
10   object as it is manipulated. The operator 14 may then grasp
hand control means 24, 26 located in the apparent workspace 22
to carry out the desired manipulations. The hand control
means 24, 26 at remote station 12 under instruction of the
position-following servo 45 control the manipulators 32, 34 at
15   worksite station 16, which actually manipulate the object in
workspace 30. The actual workspace 30 is thus effectively
projected back to the remote operator 14 to create the
illusion that he is reaching and looking directly into it and
controlling the object located in workspace 30. Properly
20   projected, this results in natural and spontaneous control
motions by the operator 14, even if he is located in an
another room or another extremely remote location.

The problems addressed by the present invention
arise from the situation where the camera lens 28 is not
25   placed at the same position in the real workspace 30 relative
to the manipulators 32, 34 as the eyes of the control operator
viewing the projected image in the "apparent" workspace 22
relative to the hand control means 24, 26. A solution is
provided by the present invention.
30   The telemanipulation system according to the present
invention can also be adapted to accommodate stereoscopic
viewing. Fig. 1B shows all the elements of Figs. 1A, with the
addition of a second camera lens 36 and image capture means
35. The two camera lenses 28 and 36 can be separated by about
35   10°, which is the same interocular viewing disparity that one
experiences when viewing a visual field at 40 cm separation.
The stereo image is displayed on a stereo video display
monitor 38 (e.g. using an electronically switched polarizer 37

over the screen) and viewed through cross-polarized
stereoscopic lenses 40, thus offering a natural image to the
remote operator 14 so that the operator experiences the
correct visual feedback when reaching and looking directly
5   into the actual workspace 30 and directly manipulating the
object located therein. The details of the system are
explained hereinafter.

         Fig. 2 is a diagrammatic perspective view of the
elements of the worksite station 16 in workspace 30 of the
10   telemanipulation system, showing features of Fig. 1 which are
in a control loop. The system an operator at a remote station
to manipulate objects located at a centerpoint 50 in the
workspace 30. In the monoscopic system, sensor means 21 with
camera lens 28 and image capture means 19 captures a real-time
15   image of the object. The operator 14 uses dual hand control
means 24, 26 to control left manipulator 32 and right
manipulator 34, respectively, which allow remote manipulation
of the object at the workspace 30. For hand control means 24,
26 and manipulators 32, 34, there is in this example a fixed
20   pivot point about which bidirectional angular motion can be
effected, together with a telescopic-like extension capability
for each of the manipulators and hand controllers. The
correlation between the hand control means 24, 26 and the
manipulators 32, 34, combined with the image captured by the
25   camera lens 28, provide sufficient feedback to give the
appearance to the control operator of real-time control over
the object at the workspace (further improvement is possible
with tactile feedback). Both left manipulator 32 and right
manipulator 34 are in this example raised 30° with respect to
30   an arbitrary plane of orientation, including a centerline axis
52 of the workspace 30, to simulate a typical positioning of
an object in the real local workspace 30.

         In operation, camera lens 28 is at the 0° lateral
position with respect to the centerline axis 52, such that the
35   camera lens 28 is between left manipulator 32 and right
manipulator 34. The face of the camera lens 28 is raised at
for example a 45° angle with respect to the plane containing
centerline axis 52 and baseline 53. This camera position and

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orientation is a close approximation to the actual eye
position with respect to the manipulators 32 and 34 and
represents a base or reference position. The image captured
by the camera lens 28 appears as if the operator were looking

5   at the centerpoint 50 while standing over the manipulators 32
and 34 with a 45° angle view into the workspace. Both left
manipulator 32 and right manipulator 34 appear in the bottom
of the displayed image (proximal to the operator's hand
controls), evoking a strong sense of telepresence, which means

10   that the operator senses direct control of manipulators 32 and
34, allowing control with dexterity and rapidity, particularly
where there is tactile feedback from the manipulators 32, 34
to the hand control means 24, 26.

        In a telemanipulation application in which

15   positioning of elements is difficult due to obstructions, it
is often necessary to move the camera lens 28 to different
positions result in a different view of the object at the
centerpoint 50. Referring to Fig. 3, a diagrammatic
perspective view of the elements in workspace 30 of the

20   worksite station 16 of a monoscopic telemanipulation system is
shown in which the camera lens 28 position is rotated by angle
θ 58 laterally in the horizontal plane away from the
centerline axis 52. After rotation of the camera lens 28,
left manipulator 32 and right manipulator 34 are still

25   inclined downward at a 30° angle relative to the plane
containing centerline axis 52 and baseline 53, and the camera
lens 28 is still positioned at an angle θ above the plane
formed by centerline axis 52 and baseline 53. In order to
evoke a sense of telepresence in the operator similar to the

30   case in which the camera lens 28 is positioned directly over
manipulators 32 and 34 (as in Fig. 2), according to the
invention, the captured image projected by the camera lens 28
is rotated about visual axis 54 through the center of the
camera lens 28. This compensates for rotation about

35   "vertical" axis U to effect a static reorientation of the
apparent manipulator positions.

        It should be understood that camera lens 28 and
image capture means 19 enjoy a full range of rotation about

vertical axis U, and that the angles relative to reference planes and the like of the manipulators and the camera are dictated by the constraints of the operating environment.

5   Additionally, camera lens 28 may be positioned at different angles relative to the plane formed by centerline axis 52 and baseline 53. For example, Fig. 4 shows camera lens 28 positioned at an elevation of 15° above the (arbitrary) reference plane formed by centerline axis 52 and baseline 53. In this alignment, camera lens 28 is below manipulators 32,

10   34.

If the image is purely monoscopic as depicted in Fig. 1A, the system can effect static reorientation of the manipulators 32 and 34 about an axis 54 through a point, specifically center point 50, by rotating the digital image

15   through rotation means 25. Fig. 3 shows the relevant angles of rotation. Angle Φ 56 denotes the angle of declination of the visual axis 54 of camera lens 28 below vertical axis U. Angle θ 58 denotes the rotation of camera lens 28 position in the horizontal plane (formed by lines 52, 53) away from

20   centerline axis 52 relative to the centerpoint 50.

Rotation means 25 effects static realignment of the manipulators by rotating the real-time image pixel-by-pixel by an angle approximately equal to $-\theta$, according to known methods. After this operation is complete, the left

25   manipulator 32 and right manipulator 34 appear in the bottom of the displayed image (lower half of the projected screen). The camera lens 28 remains stationary, and the displayed image is rotated through image manipulation. Note that if hand control means 24, 26 at the operator's station are positioned

30   above the viewpoint of the control operator, the rotation of the displayed image will correct the displayed image to the point where the manipulators appear in the top of the displayed image (upper half of the projected screen). In either case, the transformation of the displayed image allows

35   the operator to view the manipulators as if emerging from the operator's hand controls. The remapping of the image is effected before actual control can be effected.

10

In addition to effecting static realignment through
digital image transformation, transformation means 25 may
effect dynamic synchronization of apparent manipulator tip
positions with hand control positions by performing the
5   following coordinate transformation on the video image data.
The actual position of the manipulator tips in the workspace
30 can be transformed to an apparent position in the displayed
image so that the manipulators will appear to move as though
rigidly connected to the operator's hand controls. The
10   altering of the apparent position of the manipulator tips
improves the dexterity of the operator in handling the object
in the workspace 30. Because the end point of the end
effector of the manipulator is known, the point (a,b,c) can be
related to the angular position and length of the manipulator,
15   and the point (p,q,r) can be related to the same parameters
relative to the hand control using well-known trigonometric
relationships between vectors and their endpoints. Thus:

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$$\begin{vmatrix} p \\ q \\ r \end{vmatrix} = \begin{vmatrix} \cos\theta' & \sin\theta' & 0 \\ -\sin\theta' & \cos\theta' & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} \cos\Phi & 0 & \sin\Phi \\ 0 & 1 & 0 \\ -\sin\Phi & 0 & \cos\Phi \end{vmatrix} \begin{vmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} a \\ b \\ c \end{vmatrix}$$

(Eq. 1)

In connection with the transformation associated with the
above equation, the image is rotated by an angle θ' selected
25   by the operator to bring the apparent position of the
manipulators into substantial registration with the hand
controls. It is an observation that angle $\theta' \approx -\theta$. This
transformation describes the relationship between the position
of the point represented by the end effector means at (a,b,c)
30   (for either end effector means) relative to the point (p,q,r)
of the corresponding tip of the manipulator in the apparent
workspace in the displayed image on video display 20.

Another method of achieving static reorientation of
manipulator positions is to rotate the image capture means
35   about its visual axis. Referring again to the monoscopic
system depicted in Fig. 1A and Fig. 3, camera lens 28 is
rotated about its own visual axis 54, an axis normal to the
plane of the camera lens 28, to the point where left
manipulator 32 and right manipulator 34 appear in the bottom

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of the displayed image (lower half of the projected screen).
Note again that if hand control means at the operator's
station are positioned above the viewpoint of the control
operator, the rotation of camera lens 28 and image capture
5   means 19 will correct the displayed image to the point where
the manipulators appear in the top of the displayed image
(upper half of the projected screen).

To preserve the stereoscopic effect, in the case of
stereoscopic imaging, as depicted in Fig. 1B, rotations cannot
10   be done about separate axes through each camera lens, but
(referring to Fig. 5A and Fig. 5B) must be done in concert
about a single axis offset from either lens. Specifically,
rotation is done normal to center axis 57 passing through the
centerpoint 50 and an arbitrary point on center axis 57
15   between the stereoscopic camera lenses 28 and 36 (Fig. 5A &
5B). This axis is similar to the visual axis 54 described in
connection with Fig. 2. Referring to Fig. 5A, the lenses of a
stereoscopic device are shown in their initial position.
Center axis 57 shows the fixed relation of each lens of the
20   camera pair and is parallel to a reference axis 59 parallel to
an axis in the plane formed by manipulators 32, 34
intersecting at the centerpoint 50, where the axis is normal
to a line bisecting the manipulators and passing through the
centerpoint 50. In order to reorient the displayed image
25   through rotation of the image capture means, center axis 57 is
canted relative to a reference plane 59 passing through
centerpoint 50, which plane includes reference axis 59, as
shown in Fig. 5B.

There is a limitation on the amount of visually
30   acceptable rotation of the stereoscopic image capture means
19, 35 and the elevation of the image capture means 19, 35
relative to the plane of the manipulators 32, 34. The
elevation cannot be so great as to make it impossible to
change the relative view angle of each of the two manipulators
35   relative to one another. Clearly, if angle Φ equals 90°
elevation (where the viewing axis 54 lies in the reference
plane formed by lines 52 and 53), no useful change in the
relative view angle will be achieved by rotating the image.

At other angles of elevation, the limitation depends on the
separation angle of the manipulators 32, 34 and secondarily on
the separation of the stereoscopic lenses 28, 36.

5   In addition to achieving static reorientation of
manipulator positions by rotation of the camera lens 28, the
system can effect a dynamic realignment by performing a
coordinate transformation through translation means 25. The
actual position of the manipulator tips in the workspace 30
can be transformed to an apparent position in the displayed
10   image so that the manipulators will appear to move as though
rigidly connected to the operator's hand controls. The
altering of the apparent position of the manipulator tips
improves the dexterity of the operator in handling the object
in the workspace 30.

15   Fig. 8 and Fig. 9 depict the image 132 of a
manipulator (32) and an actual manipulator 32, respectively,
relative to a hand control 24. In this example, and comparing
Fig. 2, manipulators and corresponding controllers represented
by hand controls are of a type utilizing a single pivot point
20   151, 161 in connection with the position sensors 51, 61 with
two dimensional pivot about the point(s) and extension along
the axis of the manipulator 32. Other motions consistent with
these actuations, such as longitudinal rotation of the
manipulator about its axis is contemplated by the invention.
25   With reference to Fig. 8 and Fig. 9, movement of the hand
control 24 causes the manipulator tip 72 to move to a new
point (a,b,c) in workspace 30 such that the image 132 of the
manipulator tip 172 moves to a new point (p,q,r) in the
apparent workspace 22, that point appearing in the view of the
30   operator to be at the extended end of the hand control 24. It
may be preferable to express the servo commands relating the
hand control and the corresponding manipulator in their polar
coordinate systems (Ω, ψ, L) and (Ω', ψ', L'). These polar
coordinates and their respective points in Cartesian
35   coordinate systems are related by well-known polar to
Cartesian transformations.

          Referring again to Fig. 3, the specific angles of
rotation used in calculating the coordinate transformation are

shown. Angle Φ 56 denotes the angle of declination of the
visual axis 54 of camera lens 28 below vertical axis U. Angle
θ 58 denotes the rotation of camera lens 28 in the horizontal
plane away from centerline axis 52 relative to the centerpoint
5   50 in the workspace 30. Angle Γ 60 denotes the rotation of
camera lens 28 about its visual axis 54.

       In operation of a monoscopic telemanipulation
system, camera lens 28 and image capture means 19 are rotated
about visual axis 54 as described above. The coordinates
10   (a,b,c) in a reference orthogonal Cartesian coordinate system
of the three-dimensional workspace 30 define the actual
position of the tip of a manipulator, such as left manipulator
32. The following matrix equation relates the desired
apparent position (p,q,r in orthogonal Cartesian space) of the
15   manipulator tip in the displayed image in video display 20 to
the actual position (a,b,c) of the manipulator tip in the
workspace 30:

$$
\begin{vmatrix} p \\ q \\ r \end{vmatrix} = \begin{vmatrix} \cos\Gamma & \sin\Gamma & 0 \\ -\sin\Gamma & \cos\Gamma & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} \cos\Phi & 0 & \sin\Phi \\ 0 & 1 & 0 \\ -\sin\Phi & 0 & \cos\Phi \end{vmatrix} \begin{vmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} a \\ b \\ c \end{vmatrix}
$$

$$(Eq. 2)$$

When the manipulator tip is displayed at a position (p,q,r) in
the displayed image in video display 20, the manipulator will
25   appear to the operator as if it is actually at the end of the
operator's rigid hand control device. The coordinate
transformation improves the ease with which the operator can
handle objects in the workspace using a telemanipulation
system.

30   In the case of stereoscopic imaging, the stereo
image capture means 19, 35 is rotated relative to a reference
axis 59 parallel to an axis in the plane formed by
manipulators 32, 34 intersecting at the centerpoint 50, where
the axis is normal to a line bisecting the manipulators and
35   passing through the centerpoint 50, as shown in Fig. 5B.
Angle Γ 60 measures the amount of rotation of the stereoscopic
lenses 28, 36, and its value can be used in Eq. 2 to calculate
the proper coordinate transformation for stereoscopic viewing.

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In order to ensure that the movements of the manipulators 32, 24 in workspace 30 properly track the movements of the hand controls 24, 26 in the operator's apparent workspace 22 even without complete knowledge of all
5   angles and positions, the operator can establish a calibration reference for manipulators 32, 34 as they are viewed in the displayed image in video display 20 in connection with the position-following servo. Referring to Fig. 6A, which shows the image displayed in video display 20, a four-point
10   coordinate graphic element 62 for example in the form of a tetrahedron or cube structure in three-dimensional view may be superimposed in three-dimensional space on the stereo image display, providing a coordinate reference in the three-dimensional image space. To calibrate the position of a
15   single manipulator with respect to its corresponding hand control, the system "opens" the control loop, and the operator 14 moves hand control 24, for example, while observing the motion of the tip of manipulator 32, steering the tip until it appears to be touching a first reference point 64 of
20   superimposed graphic element 62, as shown in Fig. 6B. (Since the motion of the hand control and manipulator tip have not yet been coordinated, the alignment of the tip with the first reference point may require very deliberate effort.) The operator 14 then indicates to the system that superposition of
25   manipulator and reference point has been achieved (e.g., a "set" signal is sent to the system).

The system then locks the manipulator 32 into place, opens the control loop by decoupling it from the hand control 24 and instructs the operator 14 to release the hand control
30   24. The system adjusts the extension L (Fig. 8 and 9) of the hand control to match that of the manipulator L', by inserting the offset $\sigma_3 = L - L'$, so that when the control loop is closed, there will be no reactive motion by either device. That is, the apparent extension positions of the hand control
35   24 and manipulator 32 must be identical when compared in the control loop. The system then closes the control loop and unlocks the manipulator 32, returning control to the operator 14.

The operator then moves the hand control about its pivot point to an angular orientation (Ψ, Ω) at which the operator senses that the image of the manipulator appears to emerge from the operator's hand control. Similar to the process described above, the system computes transformations which ensure that there will be no reactive motion by either master or slave when the control loop is closed. The system calculates angular offsets $\sigma_1 = \Psi - \Psi'$ and $\sigma_2 = \Omega - \Omega'$ and transforming the apparent position of the master or the slave prior to closing the control loop. The system now records the positions in three-dimensional space of the hand control master (Ψ_1, Ω_1, L_1) and the manipulator slave $(\Psi'_1, \Omega'_1, L'_1)$.

The operator repeats the elements of this process with the remaining reference points of the superimposed graphic element 62. The system may then derive and install the following linearized equation relating incremental changes in the position of the hand control masters 24, 26 to incremental changes in the position of the manipulator slaves 32, 34, using the data sets to determine the coefficients of the equations relating the positions:

$$\Delta\Omega' = k_{11}\Delta\Omega + k_{12}\Delta\Psi + k_{13}\Delta L$$
$$\Delta\Psi' = k_{21}\Delta\Omega + k_{22}\Delta\Psi + k_{23}\Delta L$$
$$\Delta L' = k_{31}\Delta\Omega + k_{32}\Delta\Psi + k_{33}\Delta L$$

The solution to the above linearized equation is as follows:

$$
\begin{vmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{vmatrix}
=
\begin{vmatrix} \Delta\Omega'_1 & \Delta\Omega'_2 & \Delta\Omega'_3 \\ \Delta\Psi'_1 & \Delta\Psi'_2 & \Delta\Psi'_3 \\ \Delta L'_1 & \Delta L'_2 & \Delta L'_3 \end{vmatrix}
\begin{vmatrix} \Delta\Omega_1 & \Delta\Omega_2 & \Delta\Omega_3 \\ \Delta\Psi_1 & \Delta\Psi_2 & \Delta\Psi_3 \\ \Delta L_1 & \Delta L_2 & \Delta L_3 \end{vmatrix}^{-1}
$$

(Eq. 3)

The system installs these coefficient values in the coordinate transformer 43 which controls servo 45, with appropriate offsets σ_1, σ_2 and σ_3, so that there is no reactive motion when the loop is closed.

In an alternative embodiment, calibration of the manipulators is achieved through virtual movement with the assistance of the system. Referring to Fig. 6B, the system moves manipulator tip 32, rather than the operator guiding the manipulator tip 32, to one of four defined points in the three-dimensional workspace 30, such as reference point 64 as seen by the operator. Using the hand control 24, the operator 14 then dynamically calibrates the position of the manipulator

16

32 by steering an overlaid graphic dot until it appears superimposed on the manipulator tip 32. The operator 14 then indicates to the system that superposition of manipulator tip 32 and reference point 64 has been achieved, and the

5   coordinates of the manipulator 32 and hand control 24 are recorded. The process is repeated for the remaining reference points, after which the system derives and installs a coordinate transformation formula in the coordinate transformer 43, as described in the above embodiment.

10   In actual practice, it is preferable for the surgeon, rather than the system, to initiate the calibration process if the invention is being used in laparoscopic surgery. During surgery, the calibration process is being carried out within a patient's abdomen, where there is little

15   room to maneuver. Hence, automatic movements of the manipulator, however small, may be considered less desirable than operator-controlled movements.

          Another method for evoking a sense of telepresence in a telemanipulation system involves the use of a specific

20   coordinate transformation to compensate for other changes in the displayed image, such as a lateral shift or a scale change. The camera may undergo a lateral or angular displacement, causing the displayed image to shift. In addition, the camera may be capable of magnifying the object

25   in the workspace, which causes a scale change and a displacement of the apparent pivot point of the manipulator.

          Figs. 7A and 7B show the combined effect of a lateral shift of the image and a scale change brought about by magnification of the image. Fig. 7A shows a portion of the

30   displayed image, including a manipulator 32, in a two-dimensional field. The center of the image is at coordinates (0,0). The operator experiences the best possible sense of telepresence if the manipulator tip 72 at coordinates (u,v) in the image field appears to move as if it were rigidly attached

35   to the control device in the operator's hand. The control device is pivoted at point (m,n) in the figure. The manipulator lies at an angle α 74 to the y-axis, and the

distance from pivot point (m,n) to manipulator tip (u,v) is
length L 76.

Fig. 7B shows what the operator would see if the
image were magnified by a factor M. The center of the image
is shifted laterally by a distance of Δx and Δy, and the new
apparent coordinates of the manipulator tip 72 are (u',v').
In order to ensure a desired level of telepresence, angle α 74
and length L 76 are remapped through perspective correction
means 29 in the displayed image to give the operator the
impression that the manipulator tip 72 is still rigidly
attached to the hand control device. The following pair of
equations describe the remapping of angle α 74 into angle α'
78 and length L 76 into length L' 80:

$$\alpha' = \arctan \left[(u' - m) / (v' - n) \right] \quad \text{and}$$
$$L' = \left[(u' - m)^2 + (v' - n)^2 \right]^{\frac{1}{2}}$$

where:

$$u' = M(u - \Delta x) \qquad v' = M(v - \Delta y) \qquad \text{and where}$$
$$u = L(\sin\alpha) + m \qquad v = L(\cos\alpha) + n$$

When α and L are remapped according to the above equations,
the manipulator tip 72 appears in the displayed image to move
as if it were rigidly connected to the operator's hand control
device.

The above relationships can be extended to include
transformations in three dimensions in order to compensate for
displacement of the manipulators when the camera lens 28 is
rotated about its own visual axis 54, as in the embodiment
described with respect to Fig. 3. In all cases, the desired
goal of maintaining the perceived plane containing the two
manipulators coincident with the plane of the two hand
controls is achieved.

The invention has now been explained with reference
to specific embodiments. Other embodiments will be apparent
to those of ordinary skill in the art upon reference to the
present description. For example, the invention can be
extended to articulated manipulators with multiple points of
rotation and translation or with pivot points at locations not
physically attached to the manipulators. It is therefore not

intended that this invention be limited, except as indicated
by the appended claims.

WHAT IS CLAIMED IS:

1   1.   In a telemanipulation system for manipulating
2   objects located in a workspace at a remote worksite by a
3   control operator from a control operator station, said
4   telemanipulation system including a manipulator means at the
5   worksite with end effector means for manipulation of an object
6   in the workspace, controller means including hand control
7   means at the control operator station for remote control by
8   the control operator of the manipulator means, image capture
9   means for taking a real-time image of the workspace, and image
10 producing means for producing a display on a monitor for eyes
11 of the control operator, said controller means further
12 comprising:
13   means coupled to said image capture means for
14 processing the real-time image into a processed image for
15 display to the control operator wherein said image capture
16 means is at an angle and a position relative to the end
17 effector means which differs from a relative position of eyes
18 of the control operator and the hand control means, said image
19 processing means correlating image of said end effector means
20 with said hand control means.

1   2.   The system according to claim 1 wherein said
2   image processing means further comprises:
3   means for converting an actual position of the end
4   effector means in the workspace to a perceived position of the
5   end effector means in the viewable real-time image, the image
6   capture means being monoscopic and being positioned at an
7   angle θ on a reference plane, said image capture means being
8   above the reference plane in a reference space, and wherein
9   the eyes of the control operator are positioned at an angle 0°
10 relative to a base line on said reference plane, said eyes
11 being above said reference plane in said reference space, the
12 viewable real-time image being rotated pixel-by-pixel by an
13 angle θ', which is approximately equal to -θ.

1   3.   The system of claim 2, wherein coordinates of
2   said perceived position of the end effector means are
3   dynamically related to coordinates of said actual position of
4   the end effector means by the following relationship:

$$
\begin{vmatrix} p \\ q \\ r \end{vmatrix} = \begin{vmatrix} \cos\theta' & \sin\theta' & 0 \\ -\sin\theta' & \cos\theta' & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} \cos\Phi & 0 & \sin\Phi \\ 0 & 1 & 0 \\ -\sin\Phi & 0 & \cos\Phi \end{vmatrix} \begin{vmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} a \\ b \\ c \end{vmatrix}
$$

8   where
9         $[p,q,r]$ are coordinates of said perceived position,
10        $[a,b,c]$ are coordinates of said actual position,
11   angle θ is the rotation of the image capture means in a
12   horizontal plane about a vertical axis,
13   angle θ' being substantially equal to $-\theta$, and
14   angle Φ is the angle of declination below said vertical
15   axis of an axis normal to a surface of the image capture
16   means.

1   4.   The system according to claim 1 wherein said
2   image procesing means further comprises:
3   means for static realignment of the manipulator
4   means effected by rotating the image capture means about an
5   axis normal to a surface of the image capture means to a
6   position where each manipulator means appears in a viewable
7   real-time image as presented to the control operator, where
8   the hand controls are below a viewpoint of the control
9   operator.

1   5.   The system according to claim 1 wherein said
2   image processing means further comprises:
3   means for static realignment of the manipulator
4   means effected by rotating the image capture means about an
5   axis normal to a surface of the image capture means to a
6   position where the manipulator means appear in the viewable
7   real-time image as presented to the control operator, where
8   the hand controls are above a viewpoint of the control
9   operator.

1   6.   The system according to claim 4 wherein the
2 image capture means comprises:
3   a monoscopic camera, wherein rotation of the image
4 capture means is about a visual axis of said monoscopic camera
through a center of a lens of said monoscopic camera.

1   7.   The system according to claim 4 wherein the
2 image capture means comprises:
3   a stereoscopic dual aperture camera with a normal
4 axis bisecting a line between each aperture of said
5 stereoscopic camera, wherein rotation of the image capture
6 means is about a visual axis of said stereoscopic camera
7 through the center of said normal axis.

1   8.   The system according to claim 4 wherein said
2 image processing means further comprises:
3   means for translating an actual position of the end
4 effector means in the workspace to a perceived position of the
5 end effector means in the viewable real-time image such that
6 motion of the end effector means appears rigidly connected to
7 the hand control means.

1   9.   The system according to claim 8 wherein the
2 translating of said actual position to said perceived position
3 is according to the following relationship:

4
5 $$\begin{vmatrix} p \\ q \\ r \end{vmatrix} = \begin{vmatrix} \cos\Gamma & \sin\Gamma & 0 \\ -\sin\Gamma & \cos\Gamma & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} \cos\Phi & 0 & \sin\Phi \\ 0 & 1 & 0 \\ -\sin\Phi & 0 & \cos\Phi \end{vmatrix} \begin{vmatrix} \cos\Theta & \sin\Theta & 0 \\ -\sin\Theta & \cos\Theta & 0 \\ 0 & 0 & 1 \end{vmatrix} \begin{vmatrix} a \\ b \\ c \end{vmatrix}$$
6
7 where
8   [p,q,r] are coordinates of said perceived position,
9   [a,b,c] are coordinates of said actual position,
10   angle Γ is the rotation of the image capture means about
11 an axis normal to a surface of the image capture means,
12   angle Φ is the angle of declination of said normal axis
13 below a vertical axis, and
14   angle Θ is the rotation of the image capture means in a
15 horizontal plane about said vertical axis.

1   10.   For use with a telemanipulation system for
2   manipulating objects located in a workspace at a remote
3   worksite by a control operator from a control operator
4   station, said telemanipulation system including a manipulator
5   means at the worksite with end effector means for manipulation
6   of an object in the workspace, controller means including hand
7   control means at the control operator station for remote
8   control by the control operator of the manipulator means,
9   image capture means for taking a real-time image of the
10   workspace, and image producing means for reproducing a
11   viewable real-time image on a monitor for eyes of the control
12   operator, a method for dynamic calibration of the manipulator
13   means through actual movement using a control loop wherein
14   movements of the manipulator means directly follow movements
15   of the hand control means, the method comprising the steps of:
16   a)   superimposing a representation of a four-point
17   coordinate graphic element in three-dimensional space on the
18   viewable real-time image;
19   b)   causing the hand control means to move to
20   control motion of the end effector means; thereupon
21   c)   positioning the end effector means so that the
22   end effector means appear to be touching a first reference
23   point of said graphic element in the viewable real-time image;
24   d)   indicating to the system that superposition of
25   the end effector means and said first reference point has been
26   achieved;
27   e)   determining an offset by the relation $\sigma_3 = L' - L$
28   L to adjust the extension L of the hand control means to match
29   the extension L' of the manipulator means;
30   f)   causing the hand control means to move about its
31   pivot point to an angular orientation (Ψ, Ω), where the
32   manipulator means in the viewable real-time image appears to
33   emerge from the hand control means;
34   g)   determining offsets according to the
35   relationships $\sigma_1 = \Psi - \Psi'$ and $\sigma_2 = \Omega - \Omega'$ for adjusting the
36   angular orientation (Ψ, Ω) of the hand control means to match
37   the angular orientation (Ψ', Ω') of the manipulator means;

38   h)   recording a control position (Ψ,Ω,L) in three-
39 dimensional space of said hand control means;

40   i)   recording a controlled position (Ψ',Ω',L') in
41 three-dimensional space of said manipulator means
42 corresponding to the control position; and

43   j)   repeating steps a) through i) for each remaining
44 reference point, thereby establishing calibration.

1   11. The method of claim 10 further comprising the
2 step of synchronizing incremental changes in position of the
3 hand control means to incremental changes in position of the
4 manipulator means according to the following set of equations:

5      $$\Delta\Omega' \approx k_{11}\Delta\Omega + k_{12}\Delta\Psi + k_{13}\Delta L$$
6      $$\Delta\Psi' \approx k_{21}\Delta\Omega + k_{22}\Delta\Psi + k_{23}\Delta L$$
7      $$\Delta L' \approx k_{31}\Delta\Omega + k_{32}\Delta\Psi + k_{33}\Delta L$$

8 whose solution is as follows:

9
10      $$\begin{vmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{vmatrix} \approx \begin{vmatrix} \Delta\Omega'_1 & \Delta\Omega'_2 & \Delta\Omega'_3 \\ \Delta\Psi'_1 & \Delta\Psi'_2 & \Delta\Psi'_3 \\ \Delta L'_1 & \Delta L'_2 & \Delta L'_3 \end{vmatrix} \begin{vmatrix} \Delta\Omega_1 & \Delta\Omega_2 & \Delta\Omega_3 \\ \Delta\Psi_1 & \Delta\Psi_2 & \Delta\Psi_3 \\ \Delta L_1 & \Delta L_2 & \Delta L_3 \end{vmatrix}^{-1} .$$
11

1   12. For use with a telemanipulation system for
2 manipulating objects located in a workspace at a remote
3 worksite by a control operator from a control operator
4 station, said telemanipulation system including a manipulator
5 means at the worksite with end effector means for manipulation
6 of an object in the workspace, controller means including hand
7 control means at the control operator station for remote
8 control by the control operator of the manipulator means,
9 image capture means for taking a real-time image of the
10 workspace, and image producing means for reproducing a
11 viewable real-time image on a monitor for eyes of the control
12 operator, a method for dynamic calibration of the manipulator
13 means through virtual movement using a control loop where
14 movements of the manipulator means directly follow movements
15 of the hand control means, the method comprising the steps of:

1   a) causing the end effector means to move to a first
2 reference point of a selection of four points distributed in
3 three-dimensional space on the viewable real-time image;

4   b) manually moving the hand control means so that an
5 overlaid graphic dot appears superimposed on the viewable

6   image of the end effector means and said first reference

7   point;

8   c) indicating to the system that superposition of

9   the end effector means and said first reference point has been

10 achieved;

11   d) calculating an offset $\sigma_3 = L' - L$ to adjust the

12 extension L of the hand control means to match the extension

13 L' of the manipulator means;

14   e) moving the hand control means about its pivot

15 point to an angular orientation (Ψ, Ω), where the manipulator

16 means in the viewable real-time image appears to emerge from

17 the hand control means;

18   f) calculating offsets $\sigma_1 = \Psi - \Psi'$ and $\sigma_2 = \Omega - \Omega'$

19 to adjust the angular orientation (Ψ, Ω) of the hand control

20 means to match the angular orientation (Ψ', Ω') of the

21 manipulator means;

22   g) recording a position (Ψ, Ω, L) in three-dimensional

23 space of said hand control means;

24   h) recording a position (Ψ', Ω', L') in three-

25 dimensional space of said manipulator means; and

26   i) repeating steps a) through h) for each remaining

27 reference point, thereby establishing calibration.

1   13.   The method of claim 12 further comprising the

2   step of relating incremental changes in position of the hand

3   control means to incremental changes in position of the

4   manipulator means according to the following set of equations:

5                       $\Delta\Omega' \approx k_{11}\Delta\Omega + k_{12}\Delta\Psi + k_{13}\Delta L$
6                       $\Delta\Psi' \approx k_{21}\Delta\Omega + k_{22}\Delta\Psi + k_{23}\Delta L$
7                       $\Delta L' \approx k_{31}\Delta\Omega + k_{32}\Delta\Psi + k_{33}\Delta L$

8   whose solution is as follows:

9
10                $\begin{vmatrix} k_{11} & k_{12} & k_{13} \\ k_{21} & k_{22} & k_{23} \\ k_{31} & k_{32} & k_{33} \end{vmatrix} \approx \begin{vmatrix} \Delta\Omega'_1 & \Delta\Omega'_2 & \Delta\Omega'_3 \\ \Delta\Psi'_1 & \Delta\Psi'_2 & \Delta\Psi'_3 \\ \Delta L'_1 & \Delta L'_2 & \Delta L'_3 \end{vmatrix} \begin{vmatrix} \Delta\Omega_1 & \Delta\Omega_2 & \Delta\Omega_3 \\ \Delta\Psi_1 & \Delta\Psi_2 & \Delta\Psi_3 \\ \Delta L_1 & \Delta L_2 & \Delta L_3 \end{vmatrix}^{-1}$
11   .

1   14.   In a telemanipulation system for manipulating

2   objects located in a workspace at a remote worksite by a

3   control operator from a control operator station, said

4   telemanipulation system including a manipulator means at the

5   remote worksite with end effector means for manipulation of an
6   object in the workspace, controller means including hand
7   control means at the control operator station for remote
8   control by the control operator of the manipulator means,
9   image capture means for taking a real-time image of the
10 workspace, and image producing means for producing a display
11 on a monitor for eyes of the control operator, control means
12 comprising:
13   means coupled to said image capture means for
14 processing the real-time into a processed image for display to
15 the control operator wherein said image capture means is at an
16 angle and a position relative to the end effector means which
17 differs from a relative position of eyes of the control
18 operator and the hand control means, and which further differs
19 in scale and in lateral position, said image processing means
20 correlating manipulation of said end effector means with said
21 hand control means, said image processing means further
22 comprising:
23   means for performing a perspective correction in the
24 viewable real-time image following a lateral shift and a scale
25 change of the image capture means.

1   15.   The system according to claim 14 wherein said
2   perspective correction means comprises means for performing
3   transformations according to the following relationships:
4           $\alpha' = \arctan [(x' - m) / (y' - n)],$
5           $L' = [(x' - m)^2 + (y' - n)^2]^{\frac{1}{2}},$
6           $x' = M(x - \Delta x),$
7           $y' = M(y - \Delta y),$
8           $x = L(\sin\alpha) + m,$
9           $y = L(\cos\alpha) + n$
10 where
11   coordinates (m,n) describe a position of a pivot
12 point of the manipulator means before said lateral shift and
13 said scale change occur,
14   coordinates (m',n') describe a position of said
15 pivot point of the manipulator means after said lateral shift
16 and said scale change occur,

17   coordinates (x,y) describe a position of the end

18   effector means before said lateral shift and said scale change

19   occur,

20   coordinates (x',y') describe a position of the end

21   effector means after said lateral shift and said scale change

22   occur,

23   coordinates (Δx,Δy) describe the change in position

24   of the end effector means brought about by said lateral shift,

25   factor M describes the magnification factor of said

26   scale change,

27   angle α is the rotation of the manipulator means

28   about a vertical axis before said lateral shift and said scale

29   change occur,

30   angle α' is the rotation of the manipulator means

31   about said vertical axis after said lateral shift and said

32   scale change occur,

33   length L is a distance between said pivot point and

34   the end effector means before said lateral shift and said

35   scale change occur, and

36   length L' is a distance between said pivot point and

37   the end effector means after said lateral shift and said scale

38   change occur.

        16.   In a telemanipulation system for manipulating

1   objects located in a workspace at a remote worksite by a

2   control operator from a control operator station, said

3   telemanipulation system including manipulator means at the

4   worksite with end effector means for manipulation of an object

5   in the workspace, controller means including hand control

6   means at the control operator station for remote control by

7   the control operator of the manipulator means, image capture

8   means for taking a real-time image of the workspace, and image

9   producing means for producing a display on a monitor for eyes

10   of the control operator, said controller means further

11   comprising:

12   means coupled to said image capture means for

13   processing the real-time image into a processed image for

14 display to the control operator wherein said image capture

15 means is at an angle and a position relative to the end

16 effector means which differs from a relative position of eyes

17 of the control operator and the hand control means, said image

18 processing means correlating image of said end effector means

19 with said hand control means;

20   servo control means for controlling position of said

21 manipulator means;

22   first position sensing means coupled for sensing

23 position of said manipulator means in said workspace;

24   second position sensing means coupled for sensing

25 position of said hand control means at the operator station;

26 and

27   coordinate transformation means coupled to said

28 image processing means, to said first position sensing means

29 and to said second position sensing means for transforming

30 information about manipulator position, hand control position

31 and processed image position and into control signals applied

32 to said servo control means.

1   17. The apparatus according to claim 16 further

2 including:

3   third position sensing means coupled to said image

4 capture means for sensing position of said image capture means

5 at the worksite; and wherein

6   said coordinate transformation means is coupled to

7 said third position sensing means for transforming position

8 information about said image capture means into said control

9 signals.

1   18. For use with a telemanipulation system for

2 manipulating objects located in a workspace at a remote

3 worksite by a control operator from a control operator

4 station, said telemanipulation system including a manipulator

5 means at the worksite with end effector means for manipulation

6 of an object in the workspace, controller means including hand

7 control means at the control operator station for remote

8 control by the control operator of the manipulator means,

9   image capture means for taking a real-time image of the
10 workspace, and image producing means for reproducing a
11 viewable real-time image on a monitor for eyes of the control
12 operator, a method for dynamic calibration of the manipulator
13 means through actual movement using a control loop wherein
14 movements of the manipulator means directly follow movements
15 of the hand control means, the method comprising the steps of:
16   superimposing a representation of a four-point
17 coordinate graphic element in three-dimensional space on the
18 real-time image;
19   causing the hand control means to move; thereupon
20   positioning the end effector means under control of
21 the hand control means so that the end effector means appears
22 to be touching reference points of said graphic element in the
23 real-time image; and
24   establishing a tracking relationship between the
25 hand control means and the end effector means, thereby
26 establishing calibration.

1   19.   For use with a telemanipulation system for
2   manipulating objects located in a workspace at a remote
3   worksite by a control operator from a control operator
4   station, said telemanipulation system including a manipulator
5   means at the worksite with end effector means for manipulation
6   of an object in the workspace, controller means including hand
7   control means at the control operator station for remote
8   control by the control operator of the manipulator means,
9   image capture means for taking a real-time image of the
10 workspace, and image producing means for reproducing a
11 viewable real-time image on a monitor for eyes of the control
12 operator, a method for dynamic calibration of the manipulator
13 means through virtual movement using a control loop where
14 movements of the manipulator means directly follow movements
15 of the hand control means, the method comprising the steps of:
16   automatically causing the end effector means to move
17 through a preselected sequence of reference points distributed
18 in three-dimensional space on the viewable real-time image;

19   manually moving the hand control means so that an
20   overlaid graphic dot appears superimposed on the viewable
21   image of the end effector means at each of said reference
22   points;
23   registering position of the hand control means at
24   the position of each reference point; and
25   establishing a tracking relationship between the
26   hand control means and the end effector means, thereby
27   establishing calibration.

FIG. IA.

FIG. IB.
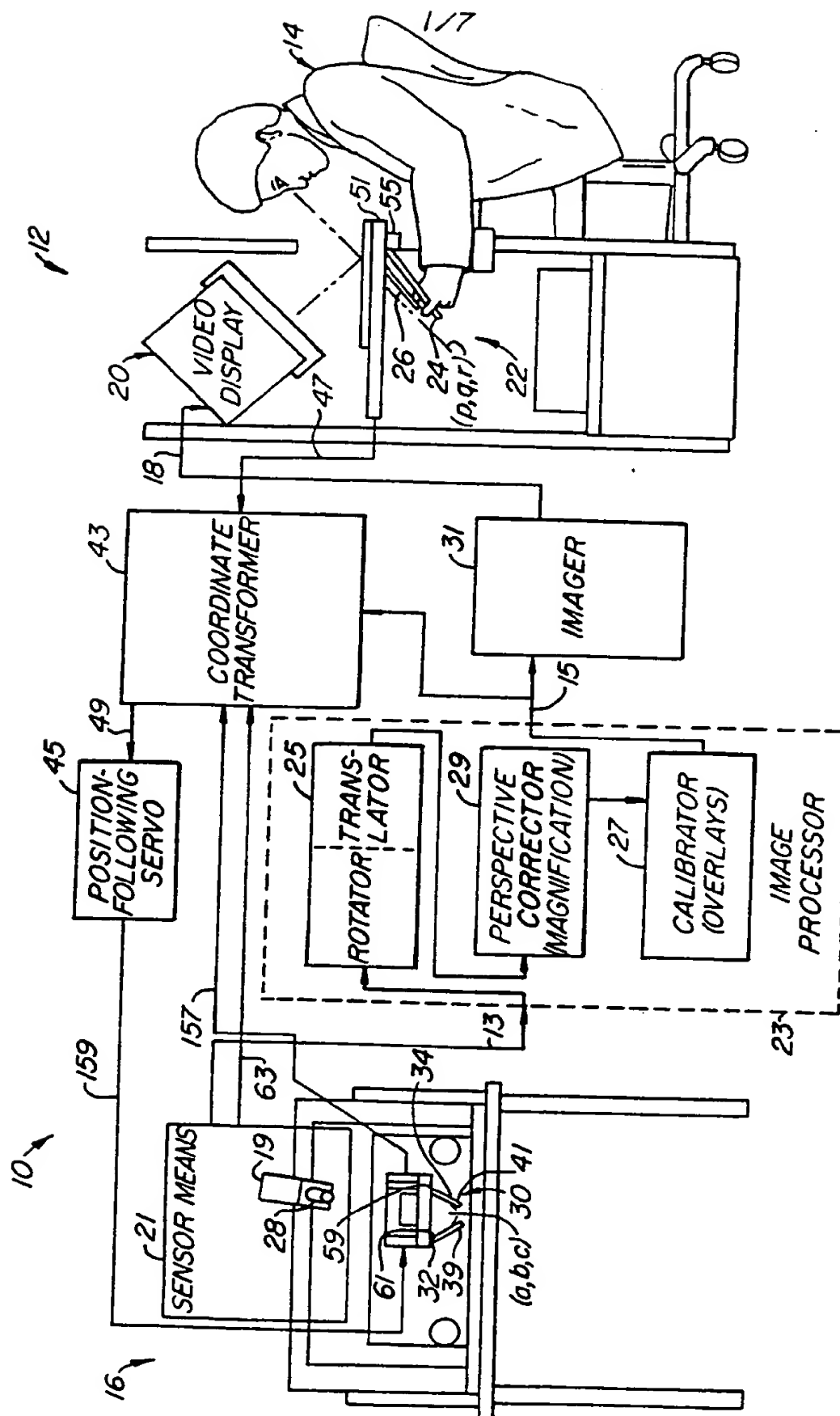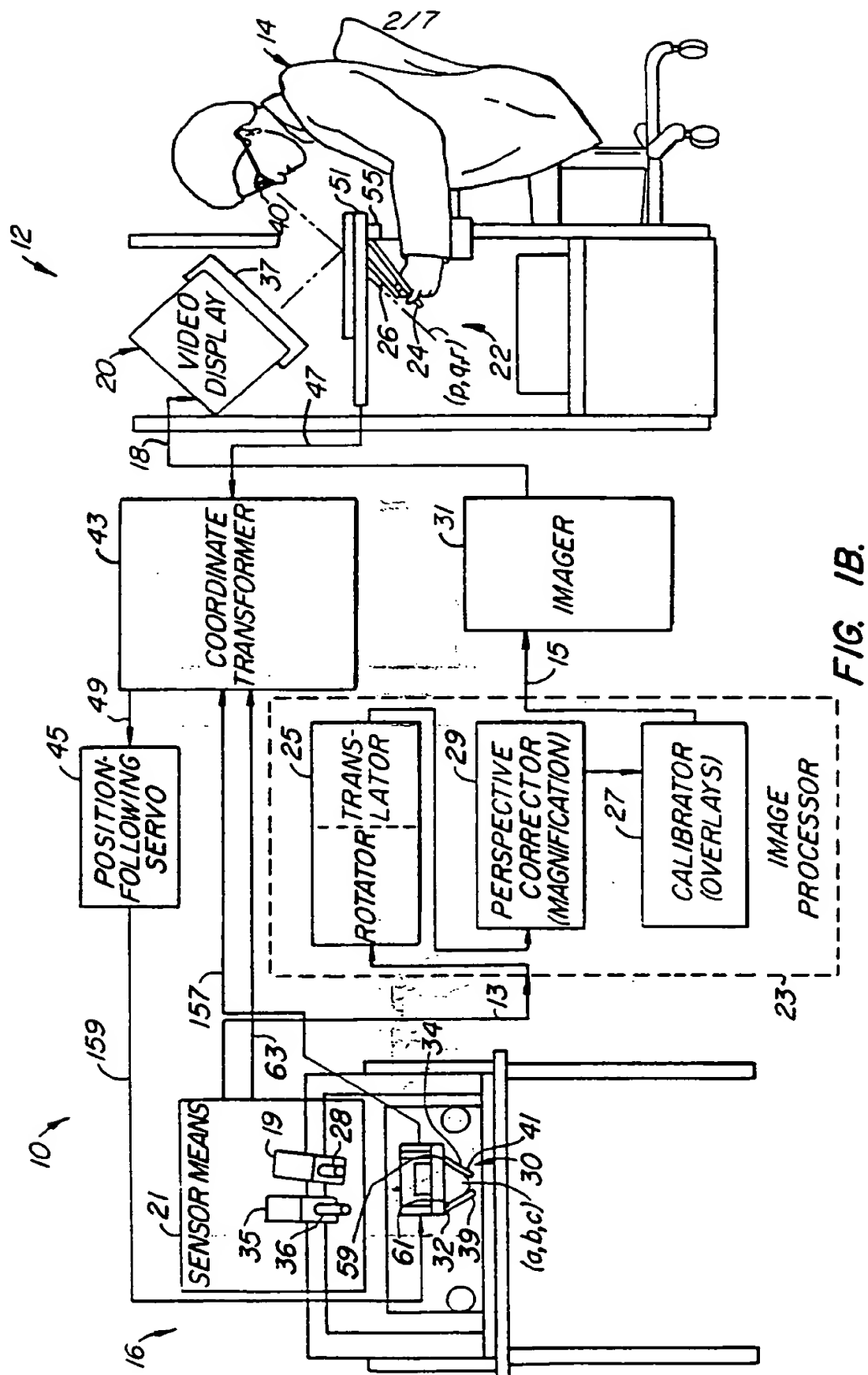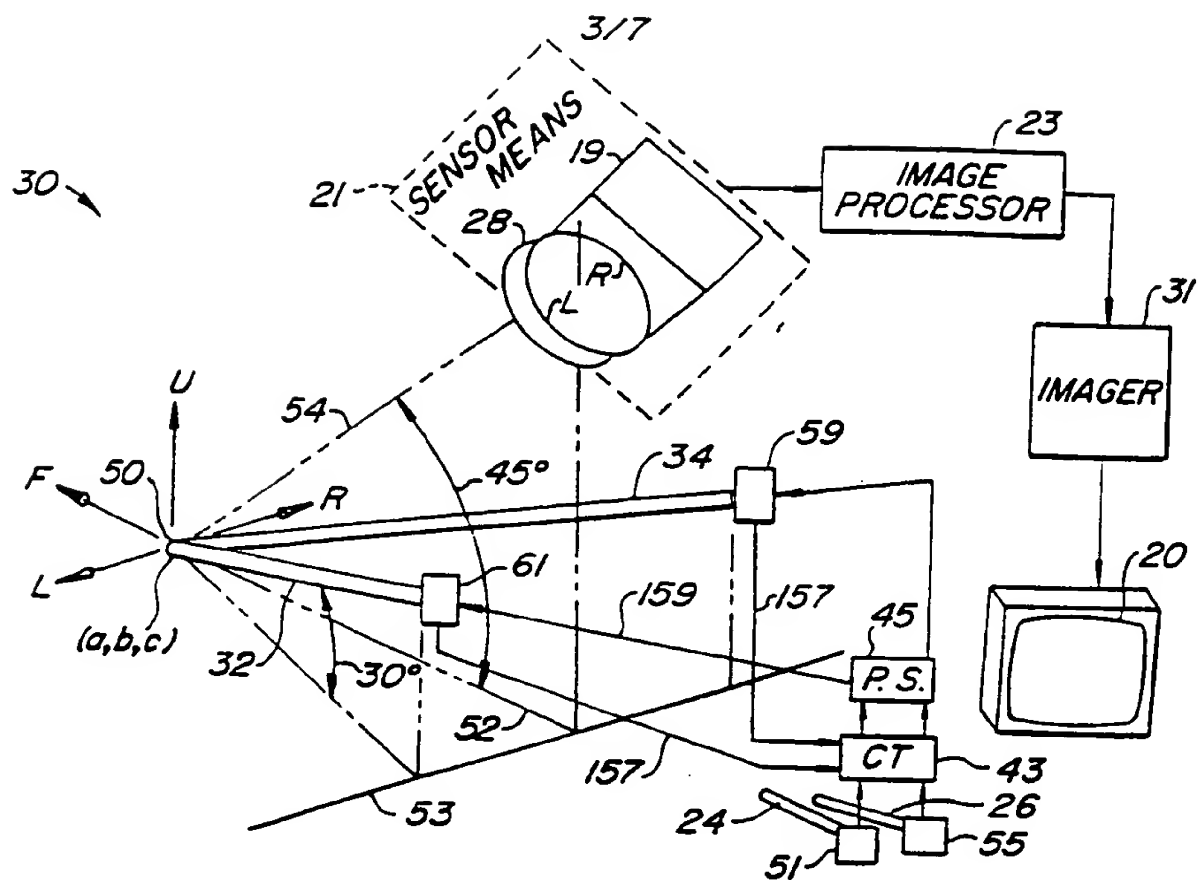
FIG. 2.
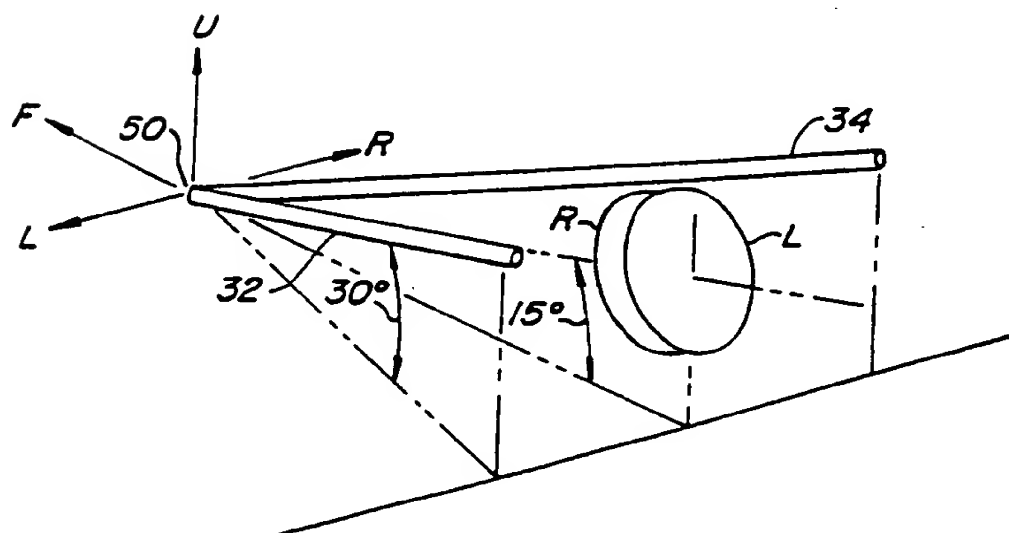
FIG. 4.
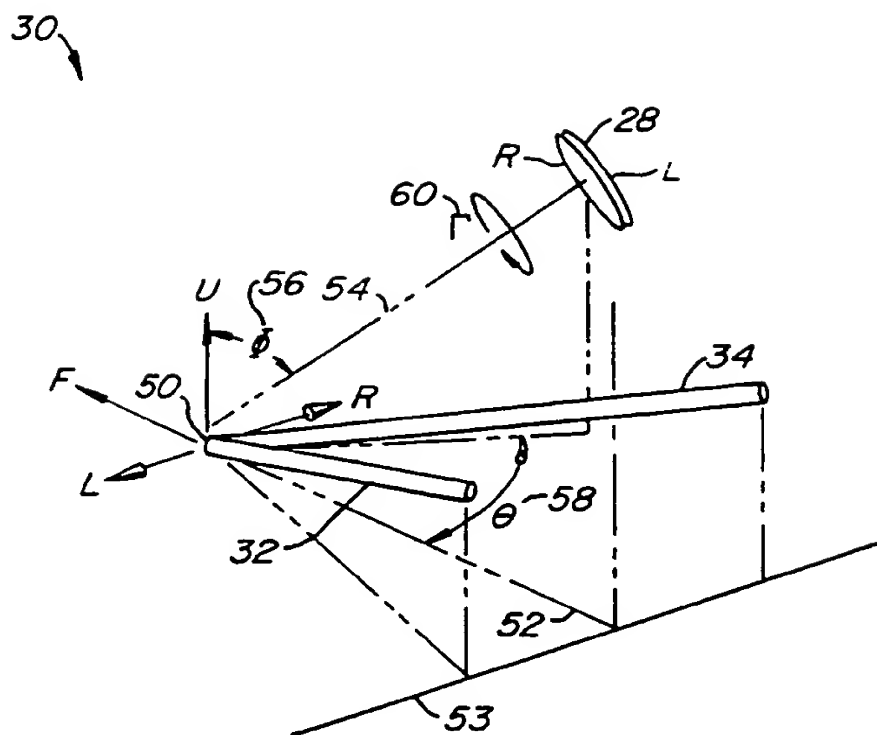
FIG. 3.
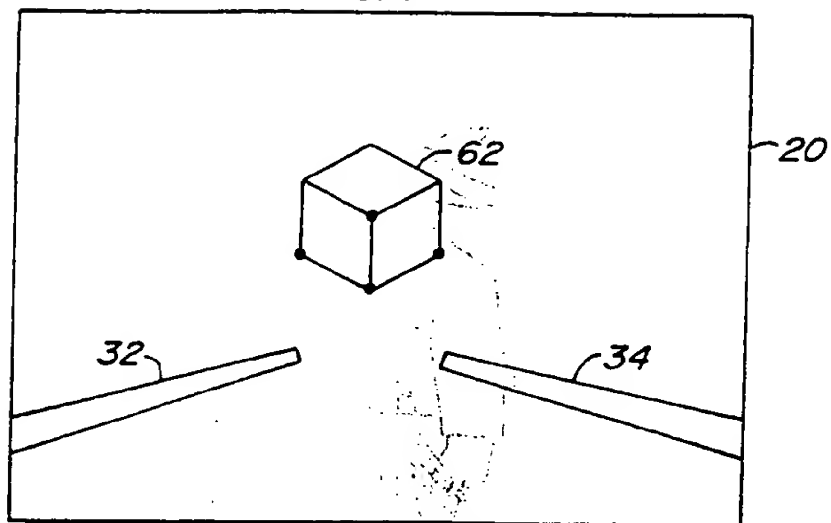
FIG. 6A.
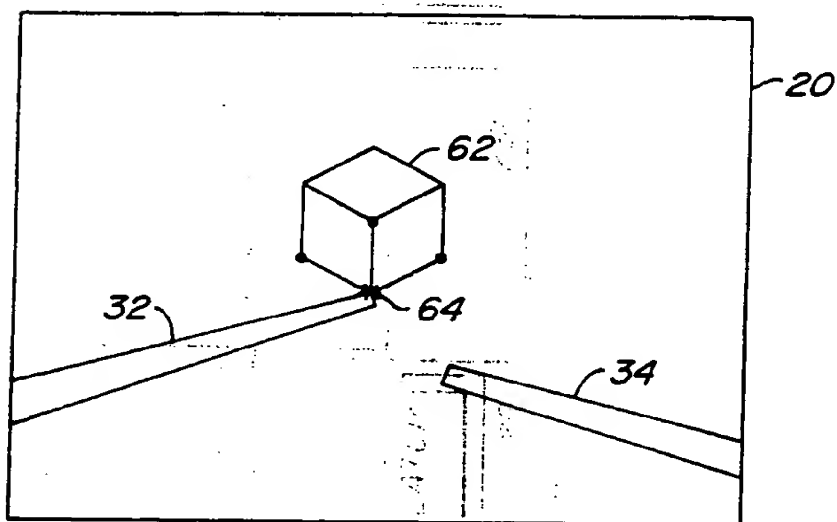
FIG. 6B.
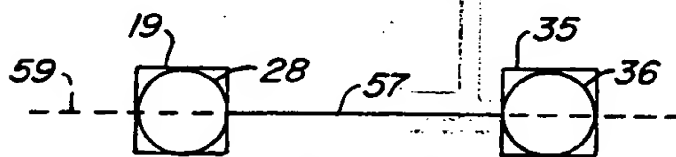
FIG. 5A.
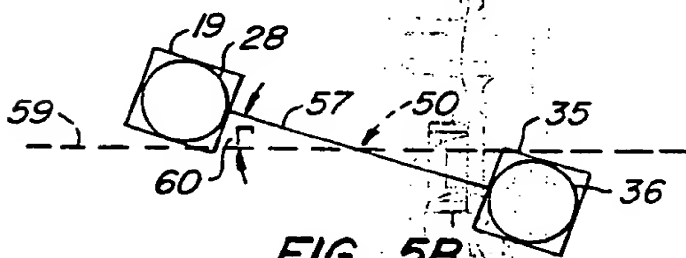
FIG. 5B.
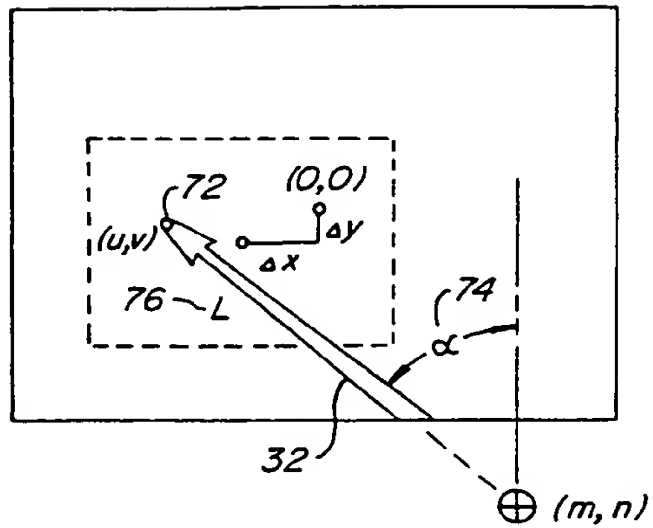
FIG. 7A.
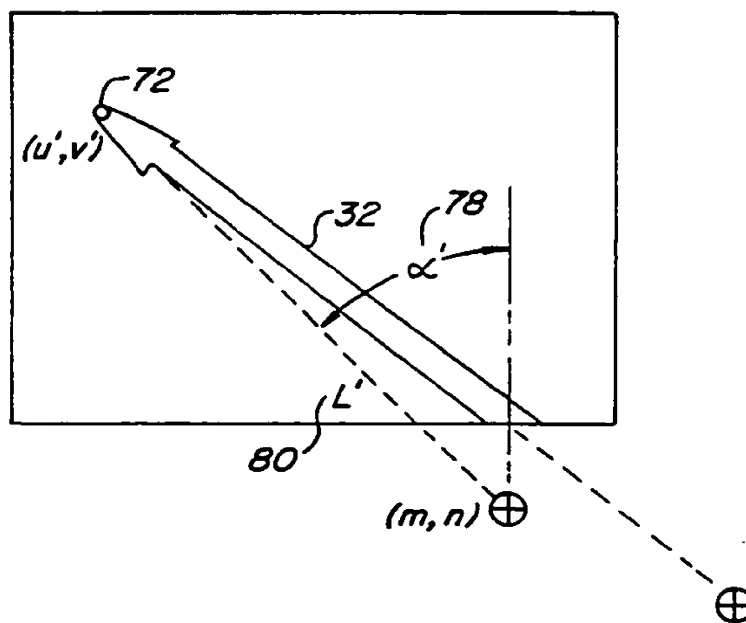
FIG. 7B.
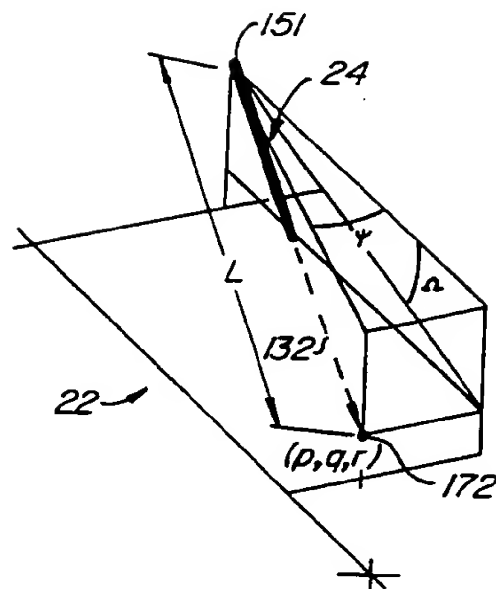
FIG. 8.
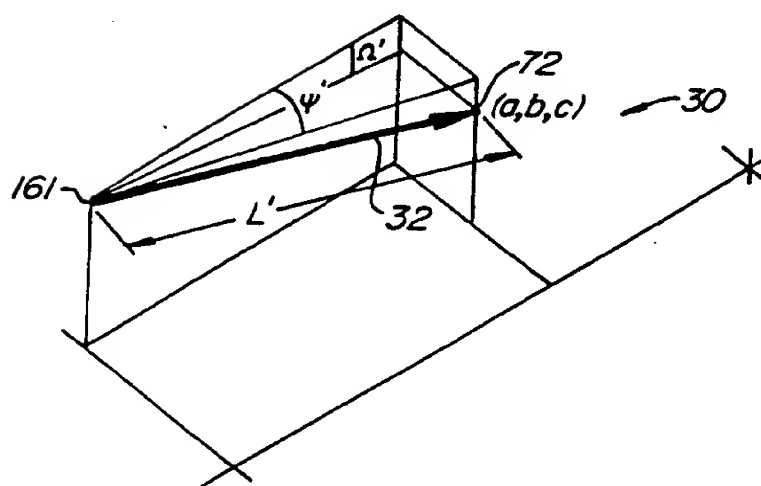
FIG. 9.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US95/05669

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : G06K 9/00; A61B 1/00

US:CL :Please See Extra Sheet.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 382/128, 153, 293, 295; 348/65; 364/413.13, 413.22; 128/4, 6; 395/95, 137, 138, 924

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y	US, A, 5,182,641 (DINER ET AL) 26 January 1993, col.2, lines 40-48 and col.5, lines 3-23, col.5, lines 46-56 and col.8, lines 20-35.	1 ------------ 4-8, 14, 16, 17
X --,P Y	US, A, 5,368,015 (WILK) 29 November 1995, col.10, lines 20-32 and col.10, lines 42-47.	1, 14 ---------- 2-7, 15-17
Y,P	US, A, 5,339,799 (KAMI ET AL) 23 August 1994, col.21, lines 23-37 and col.22, lines 36-51.	1, 14-17
A	US, A, 4,853,874 (IWAMOTO ET AL) 01 August 1989, see abstract.	3, 8, 9, 15-17

☒ Further documents are listed in the continuation of Box C.   ☐ See patent family annex.

Date of the actual completion of the international search

15 JUNE 1995

Date of mailing of the international search report

07 SEP 1995

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Form PCT/ISA/210 (second sheet)(July 1992)*

INTERNATIONAL SEARCH REPORT

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	IEEE Enginering in Medicine Conference, June 1989, Bergamasco et al, "Advanced Interfaces for Teleoperated Biomedical Robots" first page col.2.	1, 14
Y	Proceedings of the First CISM-ITOMM Symposium, Vol.1, 08 September 1973, Alexander, Arthur, "Impacts of Telemation on Modern Socity", pages 122-136, especially page 132.	1, 14

A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

382/128, 153, 293, 296; 348/65; 364/413.13, 413.22; 128/4, 6; 395/95, 137, 138, 924

BOX II. OBSERVATIONS WHERE UNITY OF INVENTION WAS LACKING
This ISA found multiple inventions as follows:

Group I Claims 1-9 and 14-17, drawn to the relation between the position of the operation and the end effector of telemanipulation system. (Class 382/293)

Group II Claims 10-13 and 18-19, drawn to a dynamic calibration system and method for extablishing a tracking relationship between an end effector and the hand control. (Class 395/152)

The claims of these two groups are directed toward different invention which are not linked to form a single general concept. The claims in the different groups do not have in common the same or corresponding "special technical features".

In particular, the apparatus and processing (such as manually moving the control means so a graphic dot is superimposed on the screen) require different searches.

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